Top quark decay $t \to c b \bar{b}$ in topcolor-assisted technicolor models

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Topcolor-assisted technicolor (TC2) model predicts the existence of the top-pions and the CP-even top-Higgs with large flavor-changing couplings to the top quark, which at tree-level can mediate the top quark three-body decay $t \to c b \bar{b}$. In this work we study this decay, showing the dependence of the decay rate on the relevant TC2 parameters and comparing the results with the predictions in the minimal supersymmetric model. We find that the decay rate in the TC2 model is much larger than in the minimal supersymmetric model and, in a large part of the parameter space, the TC2 prediction may reach the detectable level of the LHC.

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I. INTRODUCTION

The top quark was discovered at the Tevatron collider, but its properties have not been precisely measured due to the small statistics of this collider. The large hadron collider (LHC) at CERN will operate as a top quark factory, producing about eight millions of top-pair events per year in its first stage, and thus will scrutinize the top quark properties [1]. Any new physics related to top quark will be uncovered or stringently constrained [2].

In the SM the extraordinary large mass of the top quark renders the GIM mechanism very effective in the top quark sector even at loop level. As a result, the top quark flavor-changing neutral-current (FCNC) interactions are extremely small in the SM [3], which implies that the observation of any FCNC top quark process could be a robust evidence for new physics beyond the SM. This has motivated intensive studies for the FCNC top quark interactions in various new physics models, such as the popular minimal supersymmetric model (MSSM) [4] and the topcolor-assisted technicolor (TC2) model [5]. The studies in the literature are so far concentrating on the loop-induced FCNC processes of the top quark. In this work we focus on the three-body decay $t \to c b \bar{b}$, which can be mediated by a charged Higgs boson in the MSSM or by a top-pion/top-Higgs in the TC2 model.

The TC2 model predicts the existence of the top-pions ($\pi_t^{\pm}, \pi_t^0$) and the top-Higgs h_t^0 at the weak scale [6]. These scalars have large flavor-changing couplings to the top quark: besides the large charge-current coupling of $\pi_t^{\pm} t \bar{b}$, the FCNC couplings $\pi_t^0 t \bar{c}$ and $h_t^0 t \bar{c}$ occur at tree-level and can also be large. These flavor-changing couplings can induce the three-body decay $t \to c b \bar{b}$ mediated by a top-pion or top-Higgs at tree level. In our study we will show the dependence of the decay rate on the relevant TC2 parameters and compare the results with the predictions in the MSSM.

This work is organized as follows. We will briefly discuss the TC2 model in Section II, giving the new couplings which will be involved in our calculation. In Section III we give the calculation results and compare with the result in the MSSM and the SM. Finally, the conclusion is given in Section IV.

II. ABOUT TC2 MODEL

To solve the phenomenological difficulties of the traditional TC theory, TC2 theory [6] was proposed by com-

bining technicolor (TC) interactions with the topcolor interactions at the TeV scale. In TC2 theory, the TC interactions play a main role in breaking the electroweak symmetry. The ETC interactions give rise to the masses of the ordinary fermions including a very small portion of the top quark mass, namely ϵm_t with a model dependent parameter $\epsilon \ll 1$. The topcolor interactions also make small contributions to the EWSB, but its main role is to give rise to the main part of the top quark mass $(1-\epsilon)m_t$.

At the weak scale the TC2 model predicts the existence of two groups of scalars from topcolor and technicolor condensations [6, 7]. In the linear realization, the scalars can be arranged into two $SU(2)$ doublets, namely Φ_{top} and Φ_{TC} [7, 8, 9], which are analogous to the Higgs fields in the two-Higgs-doublet model. The doublet Φ_{top} from topcolor condensation couples only to the third-generation quarks, whose main task is to generate the large top quark mass. It can also generate a sound part of bottom quark mass indirectly via instanton effect [6]. Since a small value of the top-pion decay constant F_t (the VEV of the doublet Φ_{top}) is theoretically favored, this doublet must couple strongly to top quark in order to generate the expected top quark mass. The other doublet Φ_{TC}, which is technicolor condensate, is mainly responsible for EWSB and the generation of light fermion masses. It also contributes a small portion to the third-generation quark masses. However, its Yukawa couplings with all fermions are small because its VEV v_{TC} is generally comparable with v_W. The flavor changing Yukawa couplings of the new scalars $\pi_t^\pm$, π_t^0 and h_t^0 are given by [6]

$$\begin{aligned}\mathcal{L} \;=\; & \frac{(1-\epsilon)m_t}{\sqrt{2}F_t}\frac{\sqrt{v_w^2-F_t^2}}{v_w}\Big(\sqrt{2}K_{UR}^{tt*}K_{DL}^{bb}\bar{t}_R b_L \pi_t^+ \\ & +\sqrt{2}K_{UR}^{tc*}K_{DL}^{bb}\bar{c}_R b_L \pi_t^+ + iK_{UR}^{tc}K_{UL}^{tt*}\bar{t}_L c_R \pi_t^0 \\ & +K_{UL}^{tt*}K_{UR}^{tc}\bar{t}_L c_R h_t^0 + h.c.\Big)\,, \qquad (1)\end{aligned}$$

where we neglected the mixing between up quark and top quark, and K_{UL}, K_{DL} and K_{UR} are the rotation matrices that transform the weak eigenstates of left-handed up-type, down-type and right-handed up-type quarks to their mass eigenstates, respectively. Their favored values are given by [6]

$$\begin{aligned} K_{UL}^{tt} &\simeq K_{DL}^{bb} \simeq 1, \qquad K_{UR}^{tt} \simeq \frac{m_t'}{m_t} = 1-\epsilon, \\ K_{UR}^{tc} &\leq \sqrt{1-(K_{UR}^{tt})^2} = \sqrt{2\epsilon-\epsilon^2}, \qquad (2)\end{aligned}$$

with m_t' denoting the topcolor contribution to the top quark mass.

The couplings of top-pion and top-Higgs with $b\bar{b}$ are given by

$$\mathcal{L}' \;=\; \frac{m_b^*}{\sqrt{2}F_t}\frac{\sqrt{v_w^2-F_t^2}}{v_w}(i\bar{b}b\pi_t^0+\bar{b}bh_t^0), \qquad (3)$$

where $m_b^*(\leq m_b)$ is the bottom quark mass created by instatons and is approximately given by

$$m_b^* \approx \frac{3km_t}{8\pi^2} \simeq 6.6\,k \text{ GeV}\,. \qquad (4)$$

To get a limit on k, we use a bottom quark pole mass of $m_b \approx 5$ GeV, so that the entire bottom quark mass would come from contribution of topcolor instantons for $k \sim 0.73$. Here we use $k = 0.61$ for $m_b = 5$ GeV. The remaining m_b contribution is assumed to come from ETC via a Yukawa coupling ϵ_b.

III. TOP DECAY $t \to c\bar{b}b$ IN TC2 MODEL

The Feynman diagrams of the process $t \to c\bar{b}b$ mediated by a top-pion or top-Higgs at tree level are given in Fig. 1. The relevant couplings can be found in Eqs.(1) and (3). The amplitude of this process is given by

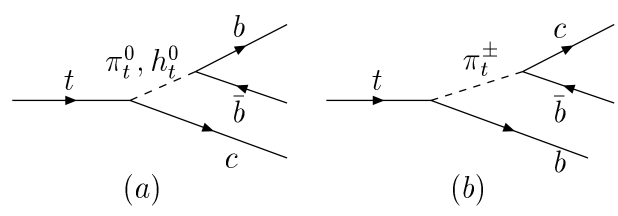

FIG. 1: Feynman diagrams of $t \to c\bar{b}b$ in TC2 model.

$$\mathcal{M} = \frac{m_t}{2F_t}\frac{\sqrt{V_W^2 - F_t^2}}{V_W} K_{UR}^{tt*} K_{UR}^{tc} \times \left[\frac{i m_b^*}{(p_b + p_{\bar{b}})^2 - m_{\pi_t^0}^2} \bar{u}_b \gamma_5 v_b \bar{u}_c P_L u_t + \frac{-m_b^*}{(p_b + p_{\bar{b}})^2 - m_{h_t^0}^2} \bar{u}_b \gamma_5 v_b \bar{u}_c P_L u_t + \frac{-2m_t}{(p_b + p_{\bar{b}})^2 - m_{\pi_t^\pm}^2} \bar{u}_b \gamma_5 v_b \bar{u}_c P_L u_t \right], \quad (5)$$

where $p_b(p_{\bar{b}})$ denotes the momentum of the b $(\bar{b})$ quark in the final state and $P_{R,L} = (1 \pm \gamma^5)/2$ denotes the chiral operator.

The decay rate of $t \to cb\bar{b}$ in TC2 model depends on the parameter ϵ (which varies in the range of $0.01 - 0.1$) and the masses of the top-pions and top-Higgs. Since the mass splitting between the neutral top-pion and the charged top-pion comes only from the electroweak interactions and thus should be small, we assume $m_{\pi_t^0} = m_{\pi_t^\pm} \equiv m_{\pi_t}$. The top-pion masses are allowed to be a few hundred GeV [10], depending on the details of the considered models. The top-Higgs mass can lie in the same range as the top-pion masses. If we assume the mass degeneracy for top-Higgs and top-pions, we can just write $M_{TC} (= m_{\pi_t} = m_{h_t})$ to denote their common mass. As for other involved parameters, we take $m_t = 172$ GeV [11], $v_W = 174$ GeV, $F_t = 50$ GeV, $m_b = 5$ GeV, $m_b^* = 4$ GeV and $m_c = 1$ GeV.

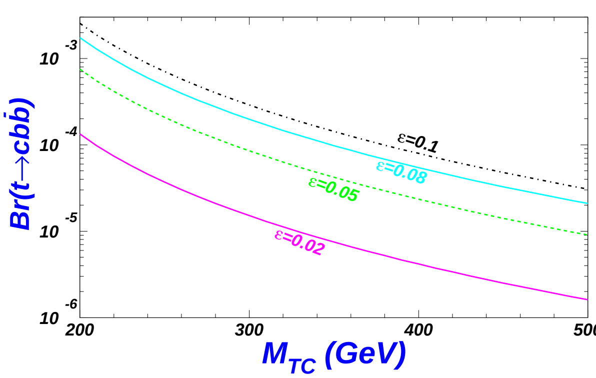

FIG. 2: The branching ratio of $t \to c\bar{b}b$ versus M_{TC} in TC2 model.

Fig.2 shows the branching ratio of $\Gamma(t \to cb\bar{b})$ as a function of the scalar mass M_{TC} for four values of the parameter ϵ. From this figure we can see that the decay branching ratio decreases with M_{TC}, showing the decoupling effects of the heavy top-pions/top-Higgs. As ϵ increases, the decay branching ratio increases. The reason is that the couplings $\pi_t^\pm cb$, $\pi_t^0 tc$ and $h_t^0 tc$ are all proportional to ϵ. Note that here we choose $M_{TC} > m_t$ so the scalars cannot be on shell. Actually, so far the top-Higgs can still be possibly lighter than top quark while the top-pions are relatively heavy [5]:

$$m_{h_t^0} > 135 \text{ GeV}, \quad m_{\pi_t^0} = m_{\pi_t^\pm} \equiv m_{\pi_t} > 220 \text{ GeV}. \quad (6)$$

So for $m_t > m_{h_t^0} + m_c$, the top-Higgs h_t^0 in $t \to ch_t^0 \to cb\bar{b}$ can be on-shell. To calculate the decay rate of $h_t^0 \to b\bar{b}$, we need to compute the total decay width of the top-Higgs. Its possible decay channels are

$$h_t^0 \to t\bar{t},\ t\bar{c},\ \bar{t}c,\ b\bar{b},\ WW,\ ZZ,\ \gamma Z,\ gg,\ \gamma\gamma. \quad (7)$$

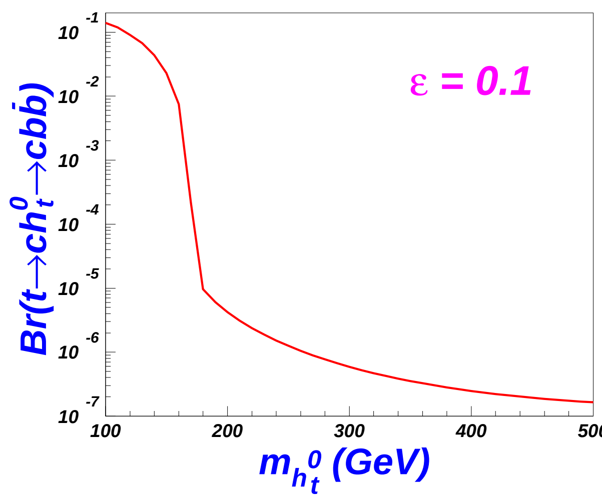

FIG. 3: The branching ratio of $t \to ch_t^0 \to c\bar{b}b$ versus $m_{h_t^0}$ in TC2 model.

In Fig.3 we plot the contribution of h_t^0 to the branching ratio of $t \to c\bar{b}b$. As expected, when h_t^0 is light enough to be on-shell, the decay branching ratio can be very large. The reason is that when h_t^0 is on-shell, the two-body decay $t \to ch_t^0$ has a large rate and, at the same time, the decay $h_t^0 \to b\bar{b}$ is the diminant mode for a light h_t^0.

Note that in the decay $t \to c\bar{b}b$ the top-Higgs contribution is dominant only for a light top-Higgs (so it can be on-shell). When the top-Higgs and top-pions are assumed to be degenerate and heavier than the top quark mass, the charged top-pion contribution is dominant.

In the MSSM the decay $t \to c\bar{b}b$ can be mediated by a charged Higgs boson. However, the coupling of the charged Higgs boson with $c\bar{b}$ is small, $\sim \frac{ieV_{cb}}{2\sqrt{2}m_W sin\theta_W} m_b \tan\beta P_L$, which is suppressed by both m_b/m_W and V_{cb}. In the SM, $t \to c\bar{b}b$ can be mediated by a W-bsoson. In Fig.4 we compare the three channels for the decay $t \to c\bar{b}b$. We see that $Br(t \to \pi_t^+ b \to c\bar{b}b)$ in TC2 model is much larger than $Br(t \to H^+ b \to c\bar{b}b)$ in the MSSM, where we take $\tan\beta = 40$, which is quite large. For a light top-pion, $Br(t \to \pi_t^+ b \to c\bar{b}b)$ can be much larger than $Br(t \to W^+ b \to c\bar{b}b)$ in the SM.

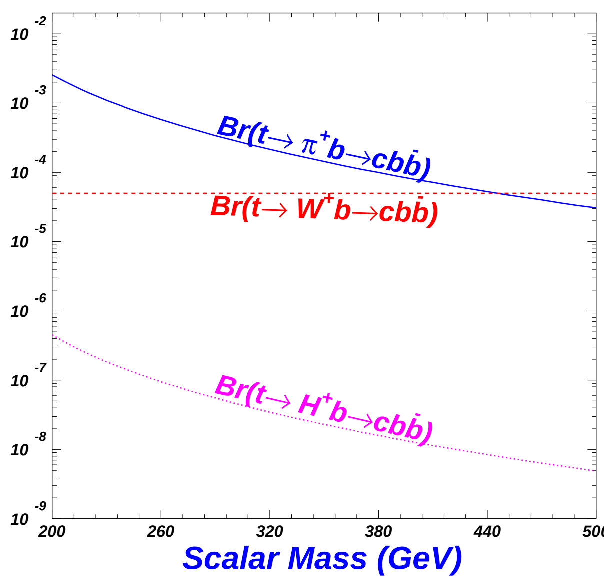

FIG. 4: The solid curve is $Br(t \to \pi_t^+ b \to c\bar{b}b)$ versus $M_{\pi_t^+}$ in TC2. The dashed line is $Br(t \to W^+ b \to c\bar{b}b)$ in the SM. The dotted curve is $Br(t \to H^+ b \to c\bar{b}b)$ versus M_{H^+} in the MSSM.

Note that the decay $t \to c\bar{b}b$ can also be mediated by a vector boson, i.e., $t \to cV \to c\bar{b}b$ $(V = g, \gamma, Z)$ with the loop-induced vertex tcV. Although such loop-induced tcV couplings can be greatly enhanced in TC2 model or the MSSM [4, 5], their contribution to $t \to c\bar{b}b$ is much smaller than the tree-level diagrams in Fig.1.

Since the decay $t \to c\bar{b}b$ can have a quite large branching ratio in the TC2 model, it would be accessible at future colliders like the LHC and the ILC. Such rare decays can be searched from the $t\bar{t}$ events with one top decaying in the rare mode while the other top having the SM decay $t \to Wb \to \ell\nu b$ $(\ell = e, \mu)$ [12]. The discovery reach of the rare top quark decays in the future colliders for $100 fb^{-1}$ of integrated luminosity is roughly given by[13]

$$\begin{aligned} LHC &: B_r(t \to cX) \geq 5 \times 10^{-5} \\ LC &: B_r(t \to cX) \geq 5 \times 10^{-4} \\ TEV33 &: B_r(t \to cX) \geq 5 \times 10^{-3} \end{aligned} \tag{8}$$

Therefore, the effects of top-pions and top-higgs in the rare top decay $t \to cb\bar{b}$ might be experimentally accessible at the LHC.

IV. CONCLUSION

We calculated the top quark three-body decay $t \to cb\bar{b}$ mediated by a top-pion or top-Higgs in the TC2 model. We showed the dependence of the decay rate on the relevant TC2 parameters and compared the results with the predictions in the minimal supersymmetric model. We found that the decay rate in the TC2 models is much larger than in the minimal supersymmetric model and, in a large part of the parameter space, the TC2 prediction may reach the detectable level of the LHC.

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